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George K. Burgess, Director

MEASUREMENTS OF THE INDEX OF REFRACTION OF GLASS AT HIGH TEMPERATURES

By C. G. Peters

SCIENTIFIC PAPERS OF THE BUREAU OF STANDARDS, No. 521

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[Part of Vol. 20]

MEASUREMENTS OF THE INDEX OF REFRACTION OF GLASS AT HIGH TEMPERATURES

BY

C. G. PETERS, Physicist
Bureau of Standards

March 18, 1926

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MEASUREMENTS OF THE INDEX OF REFRACTION OF GLASS AT HIGH TEMPERATURES

By C. G. Peters

ABSTRACT

Other measurements have shown that the expansivity and heat absorption of glass increase rapidly on heating through the annealing range which lies somewhere between 400 and 600° C., depending on the composition of the glass. The present investigation was undertaken to determine the changes in the index of refraction in the same temperature region. An interferometer method was devised by which the index of refraction can be accurately measured and any changes with varying conditions can be readily determined. The two nearly parallel surfaces of a plate of the glass are placed in contact with two interferometer mirrors in such a way that two adjacent sets of fringes are visible, one caused by light that passes through the glass and the other by light that passes through an equal distance in vacuum. The numbers of waves in this distance under the two conditions are determined from measurements made on the fringes and the approximate distance between the reflecting surfaces. The index of refraction at the initial temperature is equal to the ratio of the number of waves in the glass to the number in vacuum. The change in index produced by increasing the temperature is determined from the number of fringes that pass a reference mark on the upper interferometer plate. Measurements were made on the index of refraction and thermal expansion of nine different samples of glass, including flints, crowns, and pyrex, in the temperature region between 20 and 700° C. It was found that the glasses passed through a critical expansion region near 500° C. in which the rate of expansion increased by two to seven times. The index of refraction increased up to this critical region, then decreased in the rapid-expansion region, and increased again above the softening temperature. It should be expected that the index would decrease with the density. With every glass, however, the measured index was larger than the index computed from the density, and the difference between the measured and computed indexes increased with the temperature at a nearly constant rate. This increase in the index with temperature is probably produced by the same cause which shifts the absorption band toward the longer wave-length region.

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I. INTRODUCTION

The index of refraction of the transparent materials used in optical systems must be exceedingly uniform and accurately known. Slight variations in the index of optical glass caused by strain or strias may render prisms or lenses useless, while changes in the index because of temperature variations may interfere with the performance of the optical components of an instrument.

Measurements on the thermal dilatation of glass at high temperatures [1] made in 1918 showed that the expansivity of all the glasses investigated increased rapidly on heating through the annealing range which lies somewhere between 400 and 600° C., depending on the composition of the glass. Measurements made at about the same time by Tool and Valasek [2] showed that the heat absorption of the glass increased in the same temperature region. It seemed very probable that other properties of glass would change in this critical region so the present investigation was undertaken to determine the effect of high temperature on the refractive index. The measurements of previous observers have been confined to temperatures below 100° C., except in a few cases where they were carried to 400° C., which for most glasses is considerably below the critical region. In the present work measurements were continued beyond the critical region until the glass softened and deformed, making further determinations impossible.

1. PRISM METHOD

Measurements of the index of refraction of glass have usually been made at room temperature with the prism spectrometer. The index μ was then computed by the equation:

$$\mu = \frac{\text{Sin } \frac{\varphi + \alpha}{2}}{\text{Sin } \frac{\varphi}{2}} \qquad (1)$$

where φ is the refracting angle of the prism and α the angle of minimum deviation of the ray.

Pulfrich [3] used this method for rock salt, quartz, fluorspar, and 12 different kinds of optical glass in the temperature interval 10 to 100° C. His measurements, which were made with an Abbe autocollimating spectrometer, showed increasing dispersion with rising temperature, and indexes of refraction much larger than the values computed by any of the following formulas:

---

[1] Peters and Cragoe, B. S. Sci. Paper No. 393; 1920.
[2] Tool and Valasek, B. S. Sci. Paper No. 358; 1920.
[3] Pulfrich, Wied. Ann., 45, p. 609; 1892.

Gladstone and Dale, $$\frac{\mu-1}{d}=C \quad (2)$$

Newton, $$\frac{\mu^2-1}{d}=C \quad (3)$$

Lorenz, $$\frac{\mu^2-1}{(\mu^2+2)d}=C \quad (4)$$

where d is the density and C is a constant.

Pulfrich ascribed the divergence between calculated and observed values to the shifting of the ultra-violet absorption band toward the longer wave-length region. Therefore, on passing from one temperature to another, the measured change in index was the resultant of two opposing changes, one caused by a change in the absorption and the other by a change in density.

Reed [4] extended the work of Pulfrich to higher temperatures, using the same method and materials. He inclosed the prism in a gas-heated furnace and made measurements in the temperature interval, 20 to 430° C. As the temperature was increased, the measured indexes of all the materials, with the exception of two of the glasses, showed a continual increase relative to values computed from the density relations. With the two glasses just mentioned, the indexes increased with the temperature in the lower part of the range and decreased in the upper 60° interval. Reed attributed this latter effect to the fact that the glasses had reached their softening temperature in the upper interval, and an inverse change in the index might be expected. He predicted that similar results would probably be found for the other materials if they could be carried to their softening temperatures, which were several hundred degrees above the limit of his apparatus.

2. FIZEAU INTERFERENCE METHOD

With the interference method originated by Fizeau,[5] a change in the index of refraction of a plate of the material is determined from the expansivity of the material and the change in the number of light waves between the two opposite faces of the plate. This method was used by Rimerdes [6] to determine the change in index of refraction of crystalline quartz parallel to the axis in the temperature interval, 30 to 220° C. His results agree with those of Pulfrich and Reed, the sum of the measured change in index and the change computed from the decrease in density being found to increase with the temperature.

---

[4] Reed, Wied. Ann., **65**, p. 707; 1898.
[5] Fizeau, Ann. d. Phys., **128**, p. 564; 1866.
[6] Rimerdes, Dissertation, Jena; 1896.

II. EXPERIMENTAL METHOD

The Fizeau interferometer, which has been in use for a number of years at the Bureau of Standards for measurements of the dilatation of glass and other materials, was particularly suited for the problem outlined above. The sample in the form of a plate having two opposite faces very nearly parallel was made the separator for the two interferometer plates.

With this type of interferometer, two sets of straight fringes are observed, one produced by the light reflected from the two interferometer plates, the other by the light reflected from the two surfaces of the sample. Any change, ΔL, in the length L, of the sample causes a movement of the first set of fringes, while this change in length, together with a change, $\Delta\mu$, in the index of refraction, μ, of the glass causes a movement of the second set. The index of refraction of glass for a given temperature and wave length can be obtained from the relation:

$$\mu=\frac{N_g}{N_v} \tag{5}$$

where N_g is the number of waves of light (or the order of interference) in a length, L, of the glass, and N_v is the number of waves of the same light in an equal distance in the vacuum. The order of interference, N, in a distance, L, between two interferometer surfaces is given by

$$N=n+a=\frac{2L\mu}{\lambda} \tag{6}$$

where λ is the wave length in vacuum of the light employed, μ the refractive index of the medium for that wave length, n a whole number representing the waves in the path difference producing any fringe, a the fractional portion obtained from measurements made by means of a micrometer eyepiece in the observing apparatus, of the relative position of a reference mark and the two fringes adjacent to it. If λ, L, and μ are known with sufficient accuracy to give the correct value for n, then the order N at the reference mark is obtained at once within one to two hundredths of a wave, which is the error of measurement of a. There are a number of available light sources which emit waves, the lengths of which in vacuum are known to 1 part in 5,000,000, but L and μ are seldom known with sufficient accuracy to solve for n. It is therefore necessary to first determine L as follows: The fractional orders at the reference mark a_1, a_2, a_3, etc., for several wave lengths in vacuum λ_1, λ_2, λ_3, etc., are measured, and an approximate value, l, of the length correct within 1 or 2 μ is obtained by careful mechanical measurements. Using this value of the length we have as an approximate value for the order of λ_1,

$$\frac{2l}{\lambda_1}=n'_1+a'_1 \tag{7}$$

Replacing the computed value a'_1 by the fractional part, a_1, experimentally observed, an order

$$N'_1 = n'_1 + a_1 = \frac{2L'}{\lambda_1} \tag{8}$$

is obtained which is in error only by some whole number which should not exceed 6 or 8.

Using the approximate length, L', approximate orders for all the wave lengths employed may be calculated from the relation

$$2L' = \lambda_1 (n'_1 + a_1) = \lambda_2 (n'_2 + a'_2) = \lambda_3 (n'_3 + a'_3) = \text{etc.} \tag{9}$$

If it is found that a'_1, a'_2, a'_3, etc., agree within the experimental errors with the corresponding observed value a_1, a_2, a_3, etc., it may be concluded that n'_1, n'_2, etc., are correct; and, therefore, that L' equals the true length, L, since

$$2L = \lambda_1 (n_1 + a_1) = \lambda_2 (n_2 + a_2) = \lambda_3 (n_3 + a_3) = \text{etc.} \tag{10}$$

If there is not this agreement between the fractional parts of the two equations, it is evident that L' differs from the correct length, L, by an amount given by

$$2(L - L') = \lambda_1 y_1 = \lambda_1 (n_1 - n'_1) = \lambda_2 (n_2 - n'_2 + a_2 - a'_2) = \text{etc.}$$

where

$$y_1 = \frac{n_2 - n'_2 - y_1 + a_2 - a'_2}{\frac{\lambda_1}{\lambda_2} - 1} = \text{etc.} \tag{11}$$

and is the whole number which must be added to n'_1.

In practical application $n_2 - n'_2 - y_1 = 0$; and hence

$$y_1 = \frac{a_2 - a'_2}{\frac{\lambda_1}{\lambda_2} - 1} = \text{etc.} \tag{12}$$

The value of y_1 so determined serves to calculate a value for L, which is subject only to the errors of measurement of a_1 and λ_1, since $L = \frac{\lambda_1}{2}(n'_1 + y_1 + a_1)$. Having determined the length, the number of whole waves, n, for each wave length in vacuum where $\mu = 1$, is readily computed from equation (6). These values of n and the fractions a then give N_v of equation (5) for each wave length.

To obtain the order N_g, in glass for the different wave lengths, the fractional orders at the reference mark for systems caused by the light passing through the glass are first measured. Before computing the whole orders from equation (6), it is necessary to measure the

index of the glass with a spectrometer or refractometer. With a sample 1 mm in thickness, spectrometer values of the indexes correct within 2 in the fourth decimal place and of the dispersion correct within 2 in the fifth decimal place are sufficiently accurate to calculate the whole numbers of the order. After the correct whole numbers are found, the only uncertainties in the determination of μ, equation (5), are the errors in measurement of the fractional parts. These errors are usually about one-hundredth of a wave and correspond to an error in μ of about 5 in the sixth decimal place. Using the accurate indexes obtained from the 1 mm sample to compute the whole orders of a second sample 5 to 6 mm in length made from the same piece of glass the errors of measurement of μ are reduced to 1 in the sixth decimal place. In this case, it is necessary to control and measure the temperature of the sample to one-hundredth of a degree centigrade.

Having the index at the initial temperature, the glass is now heated to some higher temperature, causing the length to increase by some amount, ΔL. The index can then be expressed by the relation:

$$\mu_t = \frac{N_g + \Delta N_g}{N_v + \Delta N_v} \tag{13}$$

Where $N_g + \Delta N_g$ is the number of waves in the distance, $L + \Delta L$, of glass, and $N_v + \Delta N_v$, is the number of waves in the same distance in a vacuum. ΔN_g is obtained by counting the number of fringes of the system seen through the sample that pass the reference mark, and similarly ΔN_v is obtained by counting the number of fringes of the plate system that pass the same reference mark while the sample is being heated. The increase in length of the sample, ΔL, is given by the formula:

$$\Delta L = \frac{\Delta N_v \lambda_v}{2} \tag{14}$$

III. DESCRIPTION OF APPARATUS

The two plates, *A* and *B*, of the interferometer represented in Figure 1 were made of fused quartz which can be heated to 1,000° C. without serious injury to the surface. The upper surface of the base plate, *B*, was polished plane, while the lower surface was left in the ground condition to avoid regular reflection from it. Both surfaces of *A* were polished plane, but with an angle at 20′ between them so that light reflected from the upper surface could be diaphragmed out of the field of view. The central zone was then cut out of both plates, leaving them in the form of rings having 14 mm internal diameter, 26 mm external diameter, and 6 mm thickness.

The glass specimen, *S*, was made into a plate 14 mm square and 6 mm thick. Both surfaces were polished plane and at a slight angle

with each other, so that the straight fringes seen in light reflected from them had a spacing of about 2 mm.

The specimen was brought into contact at its four corners with the surfaces of the quartz plates. With this arrangement of the interferometer two sets of fringes could be seen, one caused by the light reflected from the two surfaces of the specimen, the other by the light reflected from the inner surfaces of the quartz plates, shown in Figure 1.

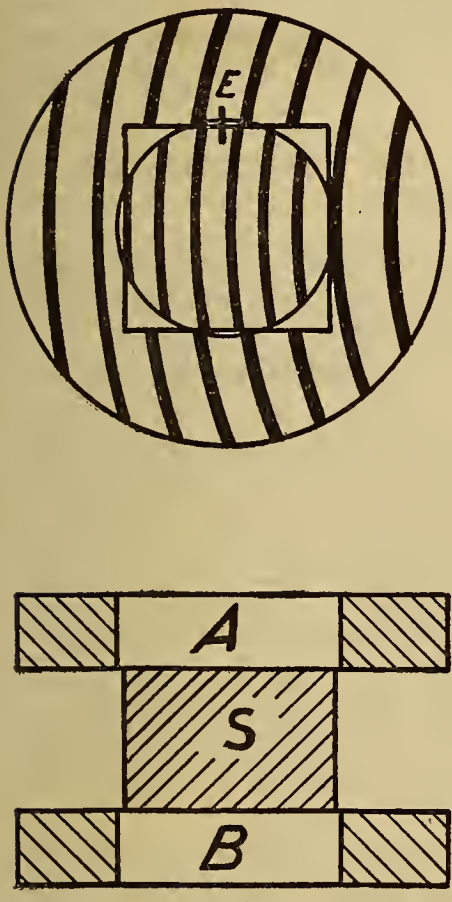

FIG. 1.—*Interferometer*

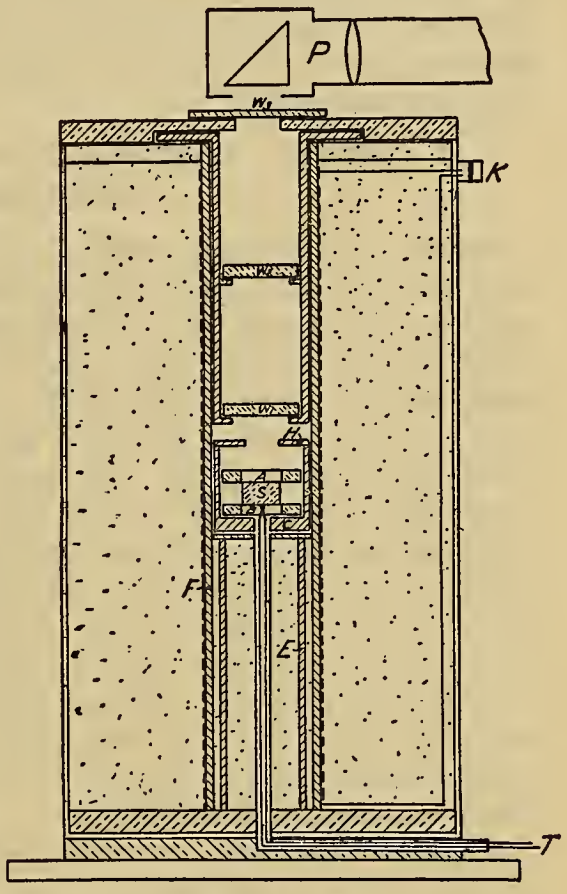

FIG. 2.—*Furnace*

Any expansion of the specimen caused the fringe system of the quartz plates to move past the reference mark, *E*, while a change in the index of the glass caused a similar motion of the fringes across the face of the specimen.

A sectional view of the furnace containing the interferometer is shown in Figure 2. A porcelain tube, *F*, wound spirally with a heating coil, *K*, is mounted in a sheet-iron jacket and surrounded with insulating material. A porcelain cup, *C*, with a cover, *H*, acts as a container for the interferometer, *ASB*, and can be lowered into the furnace by a platinum wire until it rests on the porcelain pillar,

E. The upper end of the furnace is closed by a porcelain tube containing the fused quartz windows, W_1, W_2, and W_3. A small double-bore porcelain tube which protects a calibrated *Pt, Pt–Rh* thermocouple, *T*, passes through the base of the furnace and the bottom of the cup, *C*, the thermocouple junction being adjusted so that it nearly touches the lower surface of the specimen, *S*. By this arrangement the specimen is placed very close to the couple junction and can be removed from the furnace without interfering with the adjustment of the thermocouple. The Pulfrich apparatus, consisting of a helium lamp for illuminating the interferometer and the optical arrangement necessary for measuring the position and the movement of the fringes, is represented by *P*.

IV. OPTICAL ADJUSTMENTS AND TEMPERATURE REGULATION

The sample, having been prepared in the shape of a square plate with two opposite faces nearly parallel, as described in Section III, was placed between the interferometer plates. The plates were wrung into contact with the sample so that the separation was not more than one or two hundredths of a micron. The angle between the two surfaces was sufficient to make about seven straight fringes visible across the sample. The inner surfaces of the interferometer plates, being in contact with the sample, had the same inclination; therefore, the fringes produced by the light reflected from them had the same direction as the set over the sample. When adjusted, the interferometer was placed in the cup, *C*, and lowered into the furnace. The Pulfrich apparatus was then adjusted so that both systems of fringes were visible with the line of separation extending across the center of the field. The fringe systems produced by the helium light of different wave lengths were then separated by placing the direct-vision prism in the eyepiece.

After the interferometer was placed in the furnace, at least 30 minutes time was allowed for the temperature to become constant. The fractional order of interference, *a*, at the reference mark was measured for each fringe system. The cross wires in the eyepiece were set on the fringe to the left of the reference mark, then on the reference mark, and then on the fringe to the right of the reference mark. The distance from the first fringe to the reference mark divided by the distance between the two fringes gave the value for *a*. Using these values of *a* for the different wave lengths and the measured length of the sample, N_g and N_v of equation (5), were computed. After these measurements had been made the current from a 110-volt battery was turned on and regulated so that the furnace heated at the rate of 2° C. per minute. To produce this rate

of heating required about 2 amperes at the start and 4 amperes at the highest temperature.

The heating of the apparatus changed the optical distance between the reflecting surfaces and caused the interference fringes to move across the field. As the temperature increased, the number of fringes produced by the yellow light from helium (wave length in vacuo 5877A) that passed the reference mark were counted. As every fifth fringe passed the reference mark the temperature indicated by the thermocouple was recorded. The number of fringes counted and the fraction of a fringe measured at the lowest temperature gave the change in order, ΔN_v, produced by expansion of the sample. From this the increase in thickness of the sample, ΔL, of equation (14) was computed.

During the time that these observations were being made the number of fringes in glass that passed the reference mark were also counted. At the same time that the temperature was observed, the fractional order was estimated to the nearest tenth of the fringe spacing. From this fraction, the fraction observed at the lowest temperature and the total number of fringes that had passed the reference mark, the value for the change in order, ΔN_g, of the light passing twice through the sample, was obtained. These observations were made on the fringe systems produced by helium light of the following wave lengths: (red 6680A), (yellow 5877A), (green 5017A), and (blue 4473A). With some of the samples measurements on the blue system were omitted.

With all the glasses investigated, the expansion was regular and the index increased quite uniformly up to the annealing region (which for these glasses is near 500° C.). On passing through the annealing region the usual rapid increase in the expansivity occurred, accompanied by a rapid decrease in the observed index. Heating was continued until the glass showed signs of softening. The heating current was then reduced and the furnace allowed to cool. With some of the samples, observations were continued during the cooling.

V. EXPERIMENTAL RESULTS

The dilatation or change in length of a sample in microns per centimeter was computed using equation (14).

Measured values of change in index, $\Delta\mu$, were obtained by subtracting μ, the index at the initial temperature, from the indexes at higher temperatures, $\Delta\mu = \mu_t - \mu$.

Values for the indexes at the different temperatures were also computed from the change in density, assuming the relation given in equation (2), $\frac{\mu - 1}{d} = C$, to hold.

The computed values of $\Delta\mu'$, the change in index caused by the change in density, were obtained by subtracting the index at room temperature from the computed indexes at the higher temperatures.

$$\Delta\mu' = \mu'_t - \mu$$

The difference between the measured change in index and that computed from the density is probably attributable to the change in absorption or to the same cause that produces the change in absorption; therefore, $\Delta\mu_a = \Delta\mu - \Delta\mu'$ is a relation worthy of consideration.

Table 1 gives the batch composition of six of the glasses and chemical composition of pyrex. The compositions of the other two were not determined.

TABLE 1.—*Composition*

	SiO_2	CaO	Na_2O	As_2O_5	K_2O	Fe_2O_3	Al_2O_3	ZnO	B_2O_3	BaO	PbO
1. French crown [1]											
2. Light crown, B. S. 103	67.0		12.0	0.4	5.0			1.5	3.5	10.6	
3. Barium crown, B. S. 87	47.6		2.0	1.3	6.0			9.9	4.0	29.2	
4. Borosilicate crown, B. S. 94	66.5		9.8	.2	5.9			2.0	7.8	7.8	
5. Borosilicate crown [1]											
6. Light flint, B. S. 33	54.0	2.0	1.0	.3	6.0						36.7
7. Medium flint, B. S. 110	44.3	3.0	3.5	.2	5.0						44.0
8. Barium flint, B. S. 145	58.8		1.7		8.3			2.5	1.7	14.3	12.7
9. Pyrex	80.5	.3	4.4	.7	.2	0.3	2.0		11.8		

[1] Composition not determined.

In Figures 3 to 14, inclusive, the temperatures (in degrees centigrade) are plotted as abscissas and the dilatation, ΔL (in microns per centimeter), as ordinates. The initial or room temperature ranged from 20 to 24° C. The measured changes in index of the glass represented by the curves marked "$\Delta\mu$ measured" and the differences between the measured change in index and the change in index caused by the decrease in density represented by the curves marked "$\Delta\mu - \Delta\mu'$" are also plotted as ordinates.

Table 2 gives the indexes, μ, of the different glasses at the initial temperature. Interferometer measurements were made for the four helium wave lengths on all the glasses except the French crown and one borosilicate crown. For these two glasses the spectrometer values are given.

TABLE 2.—*Indexes of the glasses at their initial temperature*

	λ=6680A	λ=5877A	λ=5017A	λ=4473A
1. French crown		1.51551		
2. Light crown, B. S. 103	1.514183	1.517189	1.522052	1.526575
3. Barium crown, B. S. 87	1.570016	1.573502	1.579204	1.584581
4. Borosilicate crown, B. S. 94	1.517174	1.520097	1.524838	1.529262
5. Borosilicate crown	1.5213	1.5240	1.5290	1.5338
6. Light flint, B. S. 33	1.580115	1.584969	1.593134	1.601067
7. Medium flint, B. S. 110	1.644374	1.650093	1.659823	1.669438
8. Barium flint, B. S. 145	1.548413	1.552169	1.558282	1.564012
9. Pyrex	1.473482	1.476067	1.480159	1.483859

The values of the dilatation and changes in index ($\lambda = 5877$A) of French crown glass are collected in Table 3. The first column gives the temperature in degrees centigrade, the second the dilatation in microns per centimeter, the third the measured change in the index, the fourth the change in index computed from the density, and the fifth the difference between the measured and computed values of the change in index. These data are shown graphically in Figure 3. The tabulated values for the other glasses have been omitted to conserve space. The results for all the glasses are represented to better advantage by the curves in the following figures:

TABLE 3.—*Data of dilatation and changes in index for* $\lambda = 5877A$ *of French crown glass*

t	ΔL	$\Delta\mu \times 10^4$	$\Delta\mu' \times 10^4$	$(\Delta\mu - \Delta\mu') \times 10^4$
20.2	0	0	0	0
100.3	8.10	+0.25	−12.52	12.75
146.5	13.34	−.04	−20.60	20.56
211.8	20.71	+.37	−31.91	32.28
248.8	24.73	+.93	−38.11	39.04
307.5	31.40	+1.99	−48.19	50.18
350.0	37.00	+1.82	−56.80	58.62
411.3	45.13	+1.22	−69.10	70.32
451.5	51.20	−.30	−78.42	78.08
499.0	61.78	−6.02	−94.41	88.41
526.6	83.87	−32.18	−127.50	95.32
550.0	100.41	−51.47	−152.17	100.70
564.2	106.44	−56.73	−161.20	104.47
575.0	109.45	−58.96	−165.61	106.65
586.3	109.97	−58.08	−166.39	108.31

Figures 3 and 4 represent almost identical results for two different specimens cut from the same sample of French crown glass. Below 480° C. the expansion was nearly linear. Between 480 and 520° C. (the annealing region) the rate of expansion increased rapidly. This rapid expansion continued to 580° C. where the glass showed signs of softening and the heating current was cut off. The index of refraction for the yellow light from helium was about constant between 30 and 450° C. even though the density of the glass had decreased. From 450 to 580° the measured index decreased rapidly. The curve marked $\Delta\mu'$ computed (fig. 3) represents the decrease in index computed from the relation $\frac{\mu - 1}{d} = C$. If the index of glass should follow this relation and decrease with the density then the measured index at each temperature is much larger than would be expected. The excess of the measured over the computed index or the increase represented by the curves marked $\Delta\mu - \Delta\mu'$ must then be ascribed to some other cause.

Pulfrich, as already noted, attributed this increase in the index with the rise in temperature to shifting of the ultra-violet absorption

band toward the longer wave-length region. This explanation is supported by the fact that the increased absorption of colorless glasses, especially of flints, for blue light, is shown by the distinctive yellow color of the glass when heated to 400° C. Gibson's [7] measurements on the spectral transmission of colored glasses showed that the absorption bands moved rapidly toward the longer wave-length region as the temperature was increased from −180 to +430° C.

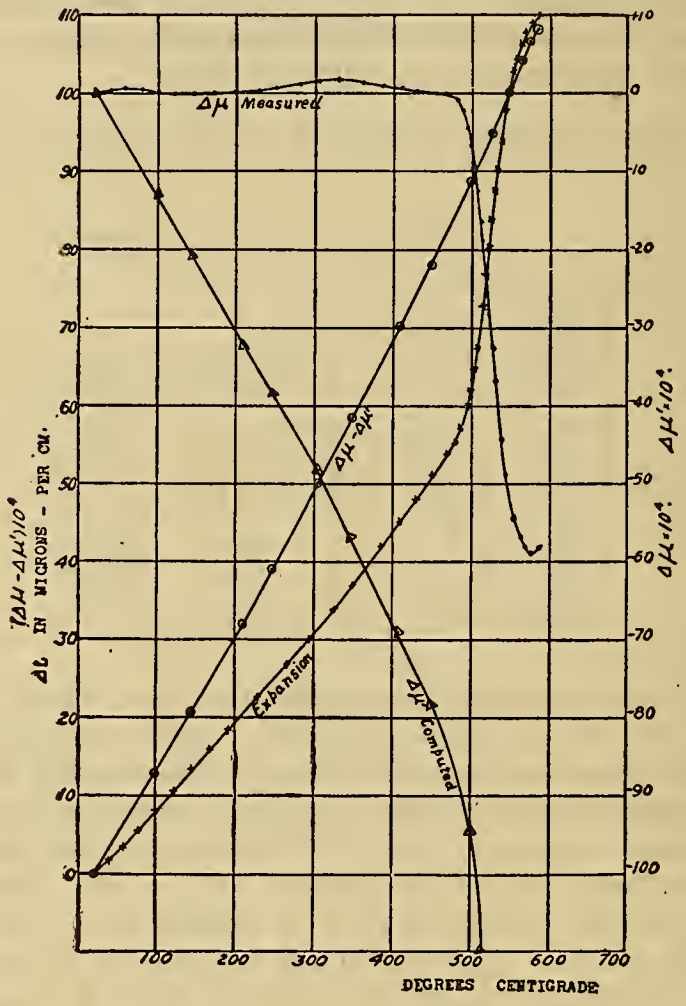

FIG. 3.—*Expansion and change in index of first sample of French crown glass*

Considering these facts it seems probable that the measured increase in the index is the result of two opposing effects, a decrease caused by a diminution in density and an increase caused by the augmented absorption. It might be more nearly correct, however, to say that this increase in index and in absorption were both produced by the same or similar causes.

[7] Gibson, Phys. Rev., 7, p. 194; February, 1916.

The difference between the measured and computed index increased at a nearly uniform rate even in the region above 480° C. (see fig. 3), where this glass expanded rapidly and where Tool and Valasek found a large increase in the heat absorption.

With a second specimen of the French crown, the results for which are shown in Figure 4, measurements were made while the glass cooled to 350° C. These measurements are reasonably reliable down to about 440° C., where the glass became rigid. They show,

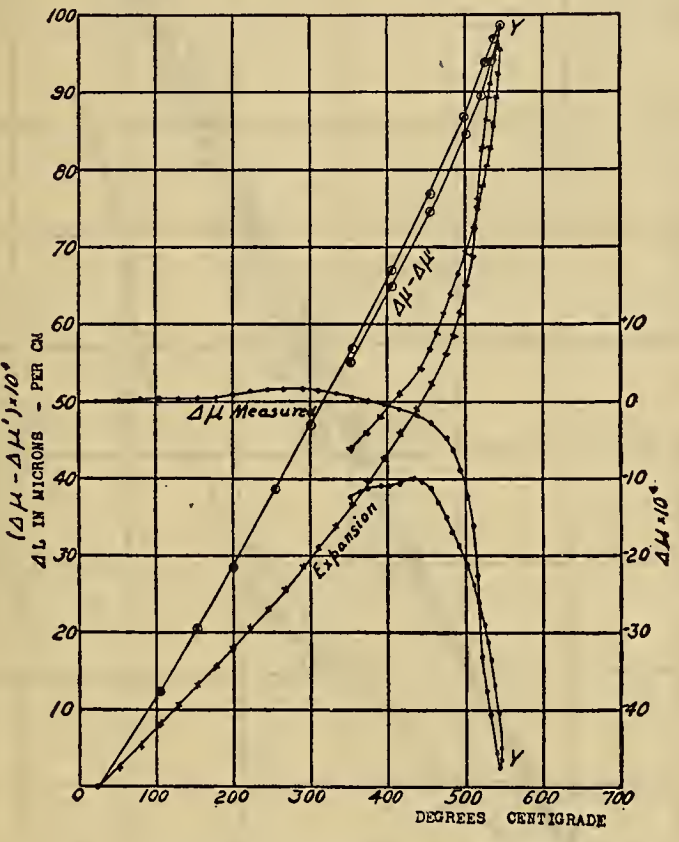

FIG. 4.—*Expansion and change in index of second sample of French crown glass*

as do the results of Figure 10, that on cooling to 30° C. the final volume of the glass was greater than the original. This agrees with the results of our previous work [8] on the volume changes in glass where the samples showed a permanent increase in volume when heated to 650° C. and allowed to cool in the furnace to 30° C. The work of Tool and Eichlin [9] shows that this increase in volume should occur because cooling in the furnace leaves the glass less thoroughly annealed than it originally was, and therefore it was in equilibrium at a higher temperature. On cooling, the measured

[8] Peters and Cragoe, B. S. Sci. Paper No. 393, p. 482; 1920.
[9] Tool and Eichlin, J. O. S. A., 8, p. 419; March, 1924.

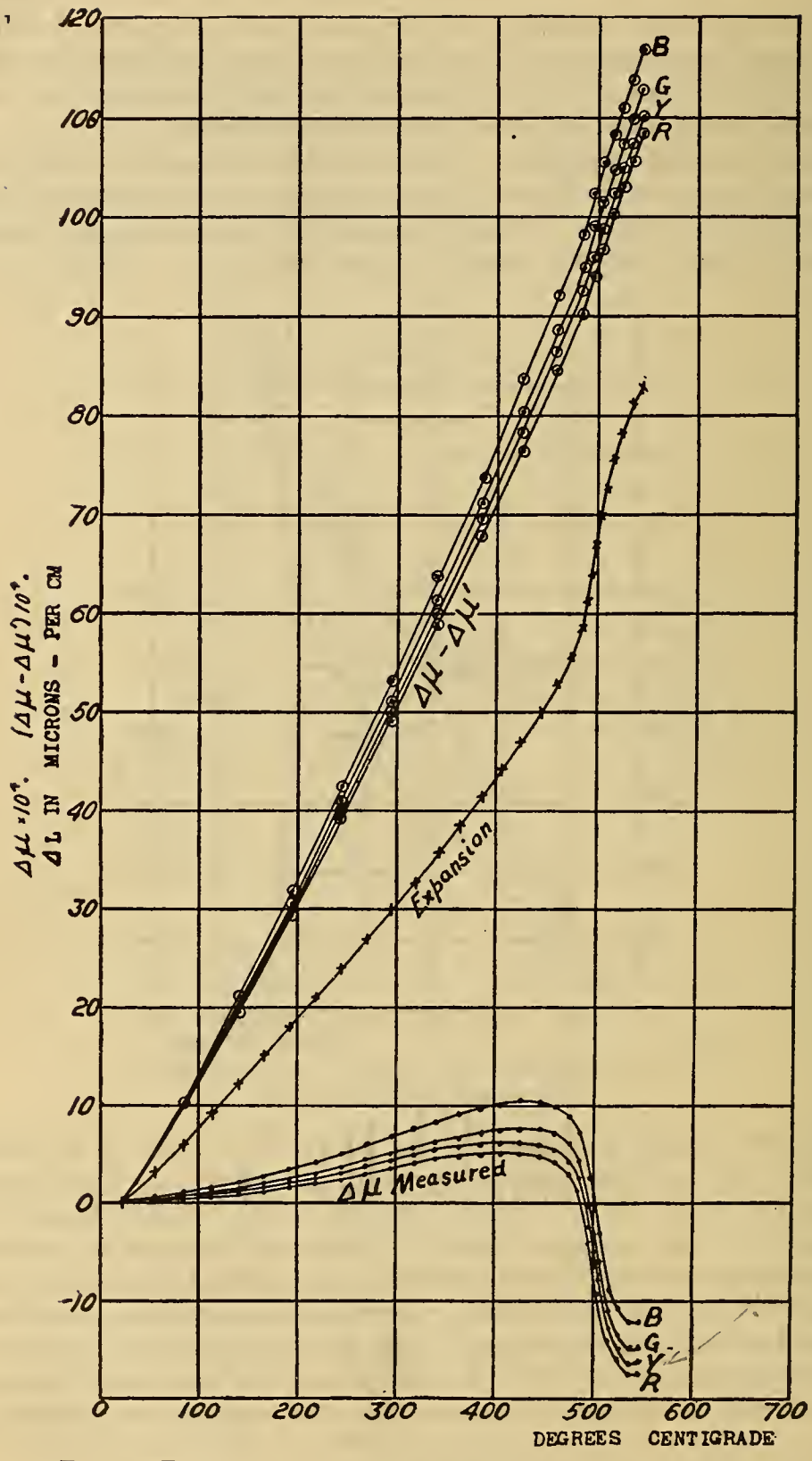

FIG. 5.—*Expansion and change in index of light crown, B. S. 103*

index showed a considerable decrease but the quantity $\Delta\mu - \Delta\mu'$ showed no appreciable change. This quantity should show no great change since the shift in the position of the absorption band

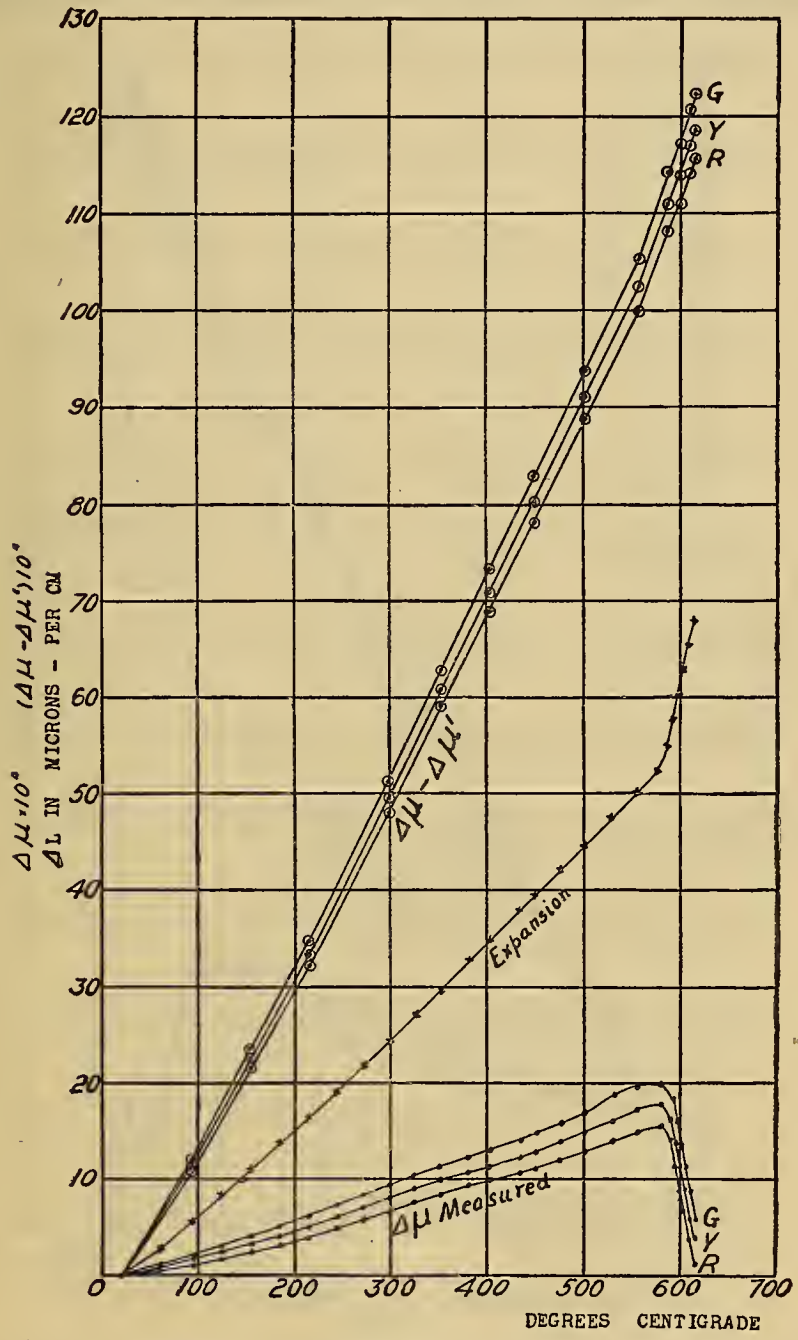

FIG. 6.—*Expansion and change in index of barium crown, B. S. 87*

is probably small for the relatively slight increase in the equilibrium temperature.

Figure 5 represents the results of measurements on a sample of light crown glass made at the Bureau of Standards. Measurements

were made with the red, yellow, green, and blue light from helium. The measured change in index for each wave length increased with the temperature to 450° C. and then decreased through the region of rapid expansion. The separation of the curves shows the effect on

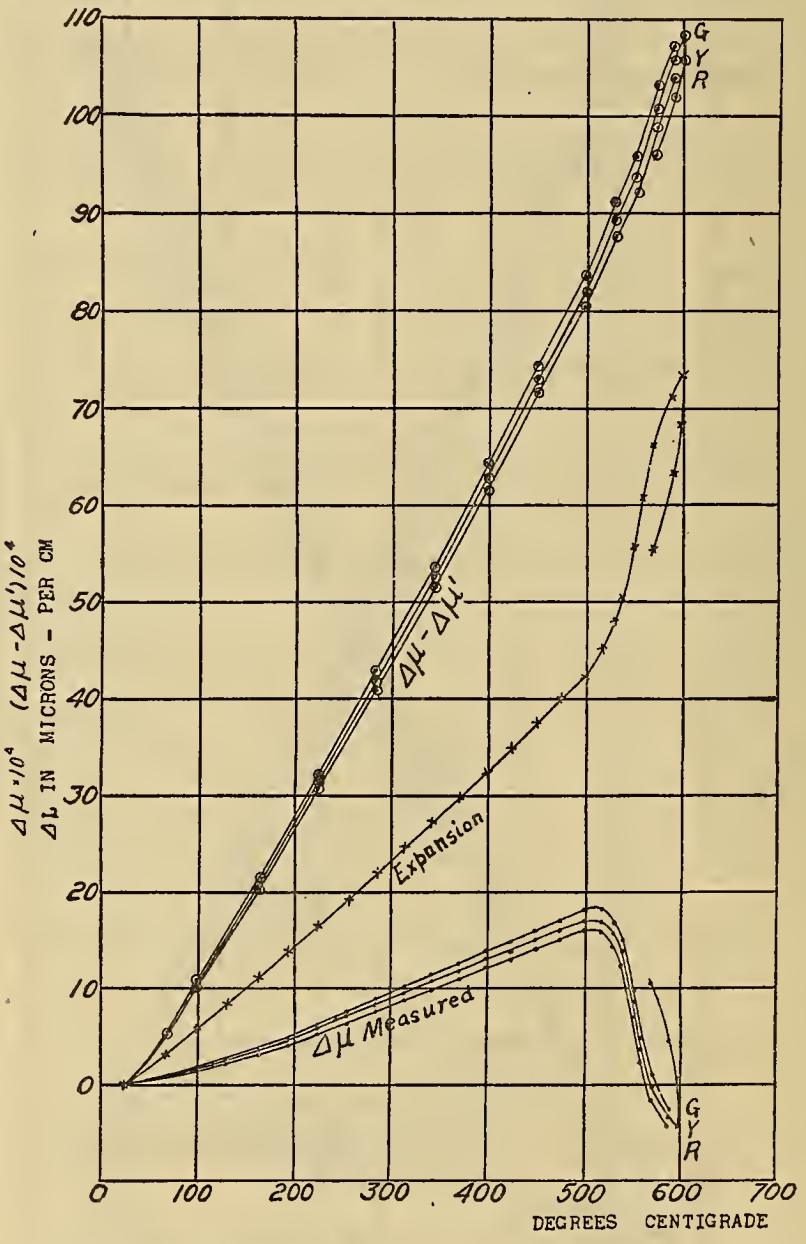

FIG. 7.—*Expansion and change in index of borosilicate crown, B. S. 94*

the dispersion. The ratio of the change in index to the index at room temperature is considerably larger for the blue than for the red light. Similar results from a sample of barium crown are shown in Figure 6.

Figure 7 represents the measurements on a sample of borosilicate crown glass made at the Bureau of Standards, and Figures 8 and 9 the results from two specimens from a sample of borosilicate crown glass made by the Pittsburgh Plate Glass Co. The results from the

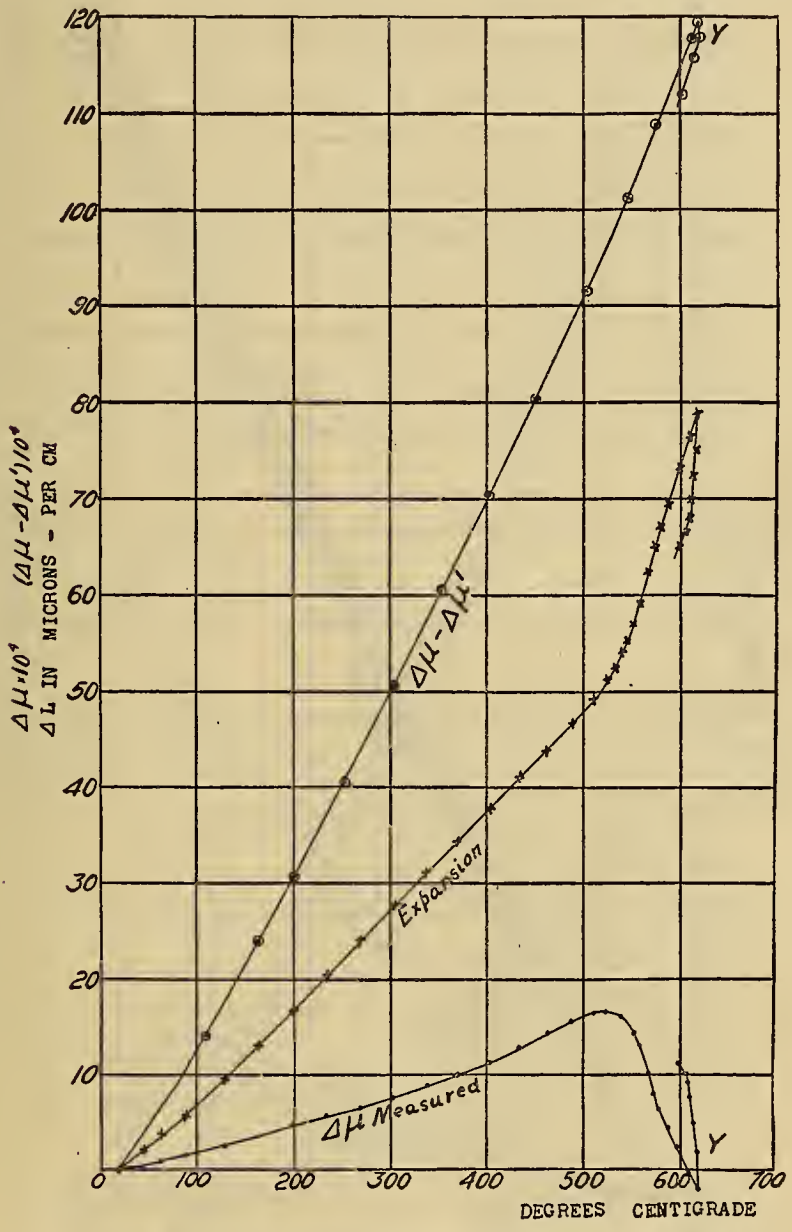

FIG. 8.—*Expansion and change in index of first sample of borosilicate crown, commercial*

latter two specimens are almost identical and show, as do Figures 3 and 4, the reproducibility of the measurements.

The results from measurements of light flint, medium flint, and barium flint glasses are represented by the curves of Figures 10 to 13, inclusive. These glasses have a yellow color which shows that

they absorb a large part of the blue light even at room temperature. The change in index with temperature was larger for these glasses

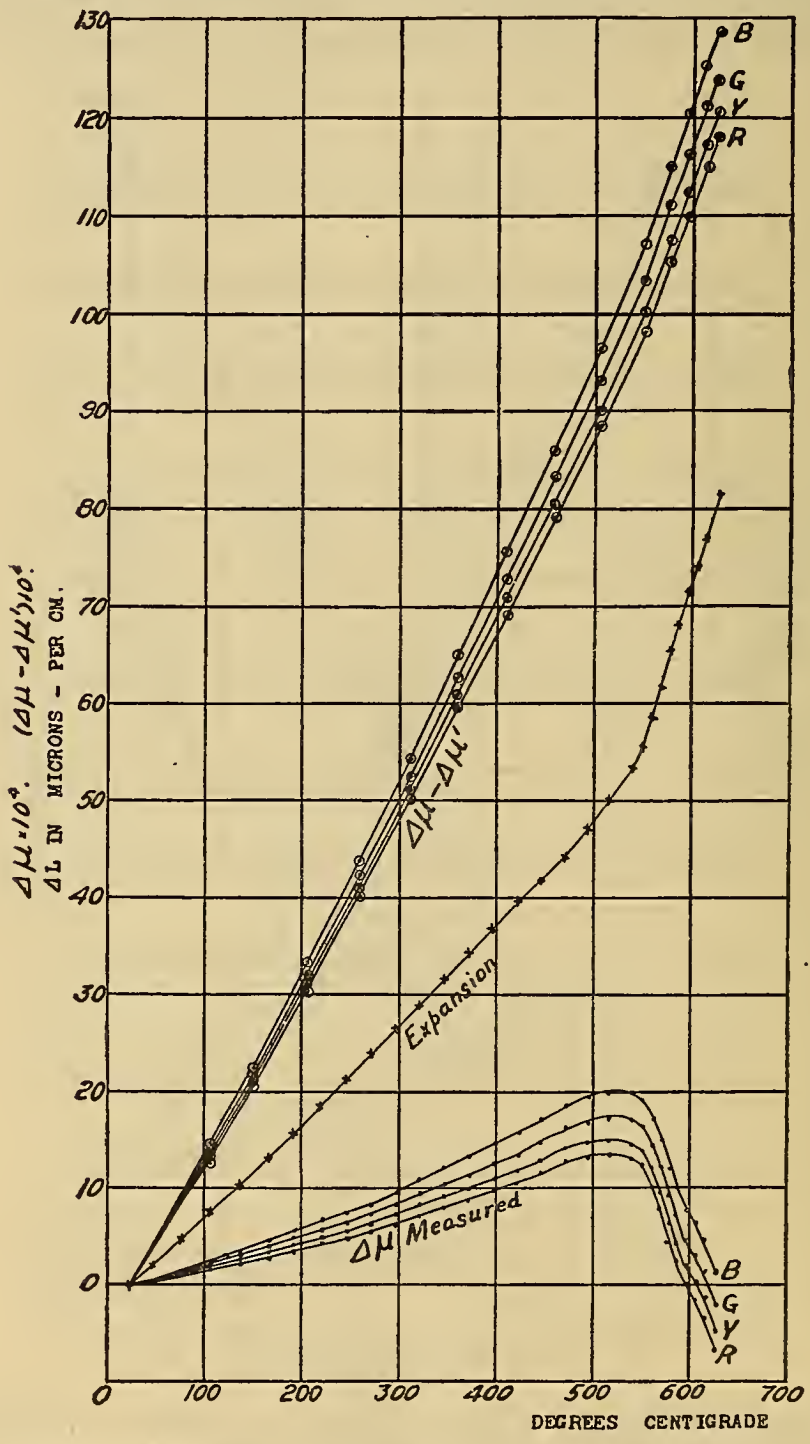

FIG. 9.—*Expansion and change in index of second sample of borosilicate crown, commercial*

than for the crowns. With the glass shown in Figure 10 measurements were continued with the yellow light while the sample cooled to

340° C. With sample shown in Figure 12 an attempt was made to continue the measurements for 40 or 50° above the softening temperature of the glass. Above 550° C. this glass softened so much that the interferometer plate settled into the sample, making it impossible to meas-

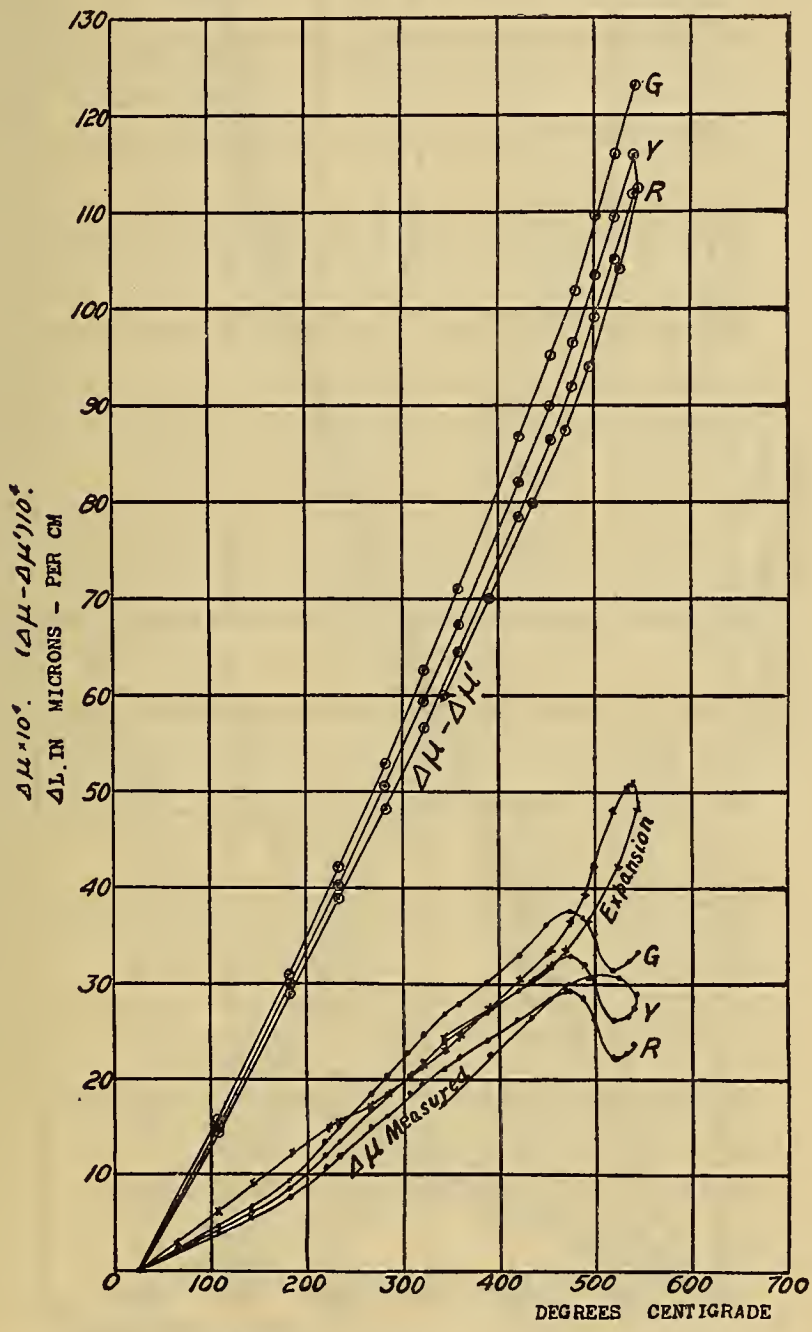

FIG. 10.—*Expansion and change in index of light flint, B. S. 33*

ure the correct value of ΔN_v; therefore, the results in this region are not very significant. The fringes seen through the sample, however, continued to move in their original direction, while those seen between the quartz plates reversed the direction of their motion.

The upward turn of the curves representing $\Delta\mu$ (measured) of these three glasses just before the softening temperature is reached indicates

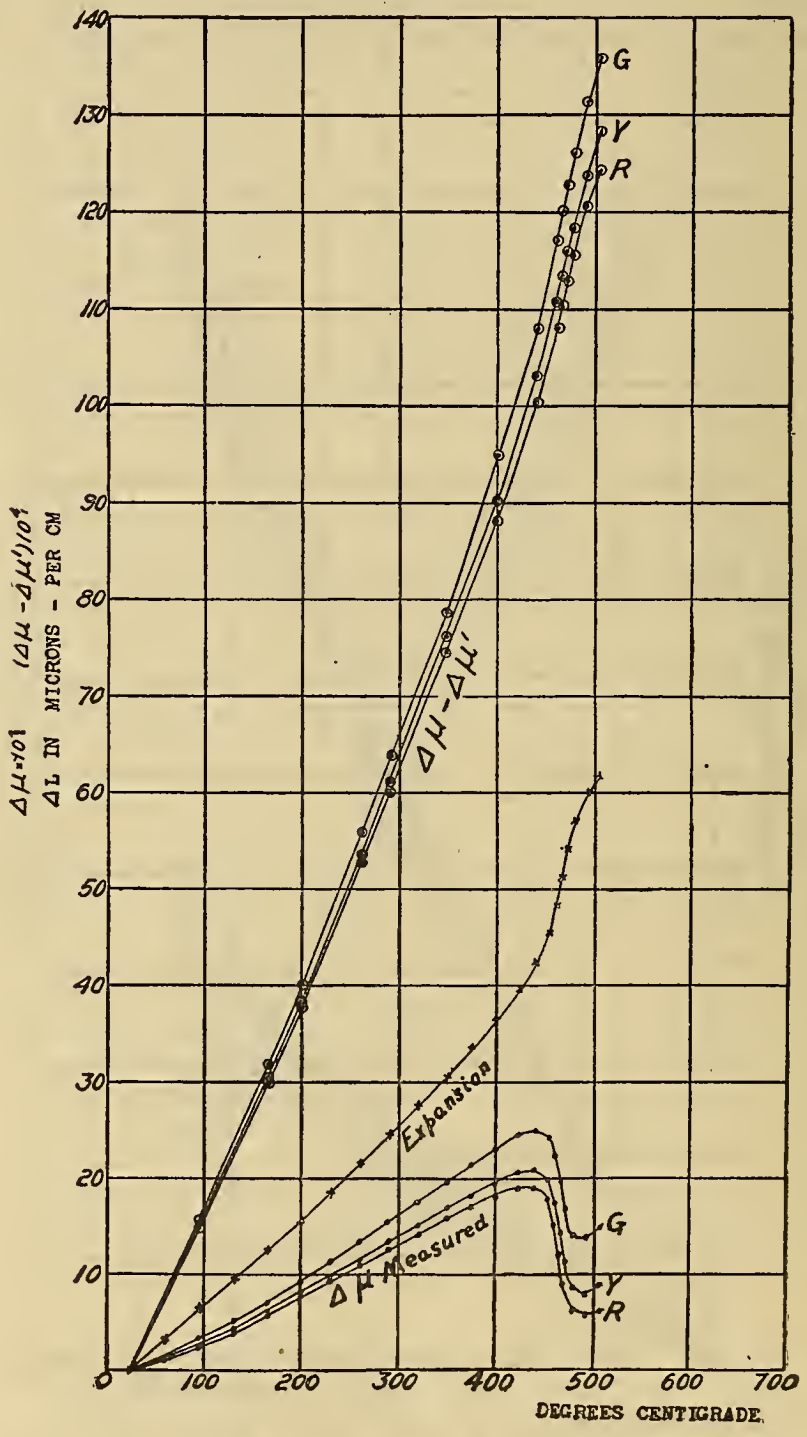

FIG. 11.—*Expansion and change in index of medium flint, B. S. 110*

that their indexes increased at about the same rate above the softening temperature as they did below the annealing range. It is probable that by modifying the method and apparatus correct measure-

ments of ΔN_v can be made above the softening temperature, so that reliable values for both the thermal expansivity and refractive index can be obtained for that temperature region.

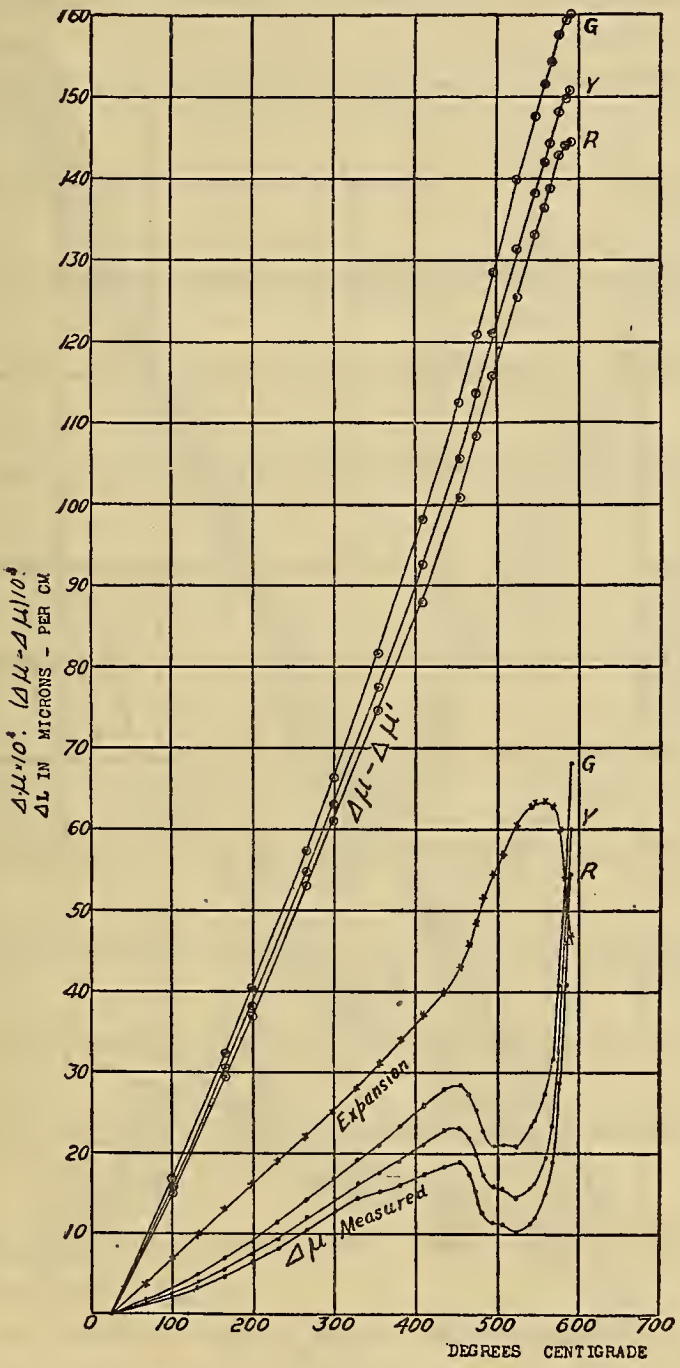

FIG. 12.—*Expansion and change in index of medium flint, B. S. 110*

Figure 14 represents the measurement made on a sample of pyrex glass which has a very low expansivity, probably because of its high silica content. The increase in the expansivity through the annealing

region was not so pronounced as for the other glasses. Above 620° C. the glass softened very slowly, as is shown by the gradual fall in the expansion curve, thus allowing the measurements to be continued to 720° C., which is about 100° above the softening temperature. The

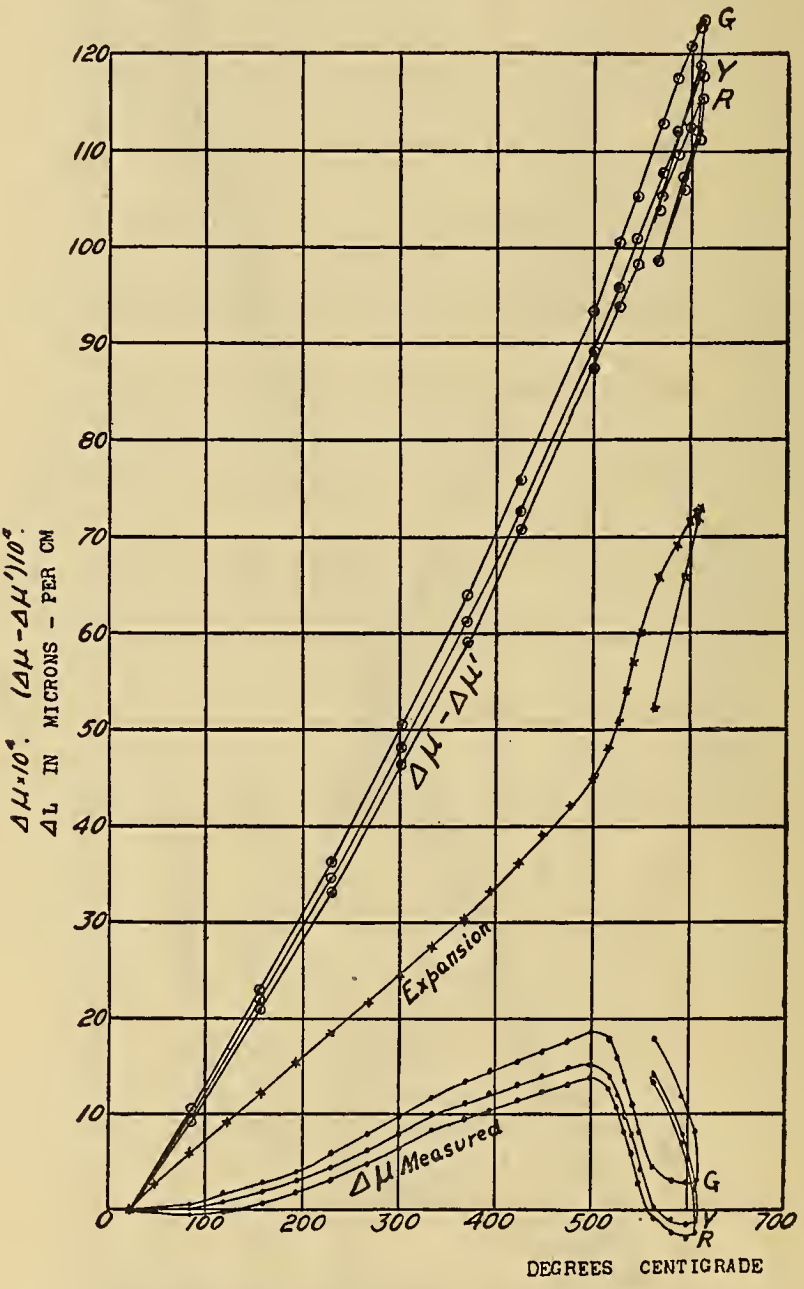

FIG. 13.—*Expansion and change in index of barium flint, B. S. 145*

measured index increased very little through the annealing range and rapidly again above 600° C. This rapid increase in $\Delta\mu$ above 600° C., which is similar to the increase above the softening temperature shown by the glasses of Figures 10 to 13, is caused in part by the

decrease in ΔN_v, resulting from the sinking of the interferometer mirror into the sample at the points of contact. In our work on the thermal dilatation of glass (l. c.), measurements of this deformation of the sample were made on three glasses while the temperature was held constant at different points above the softening temperature.

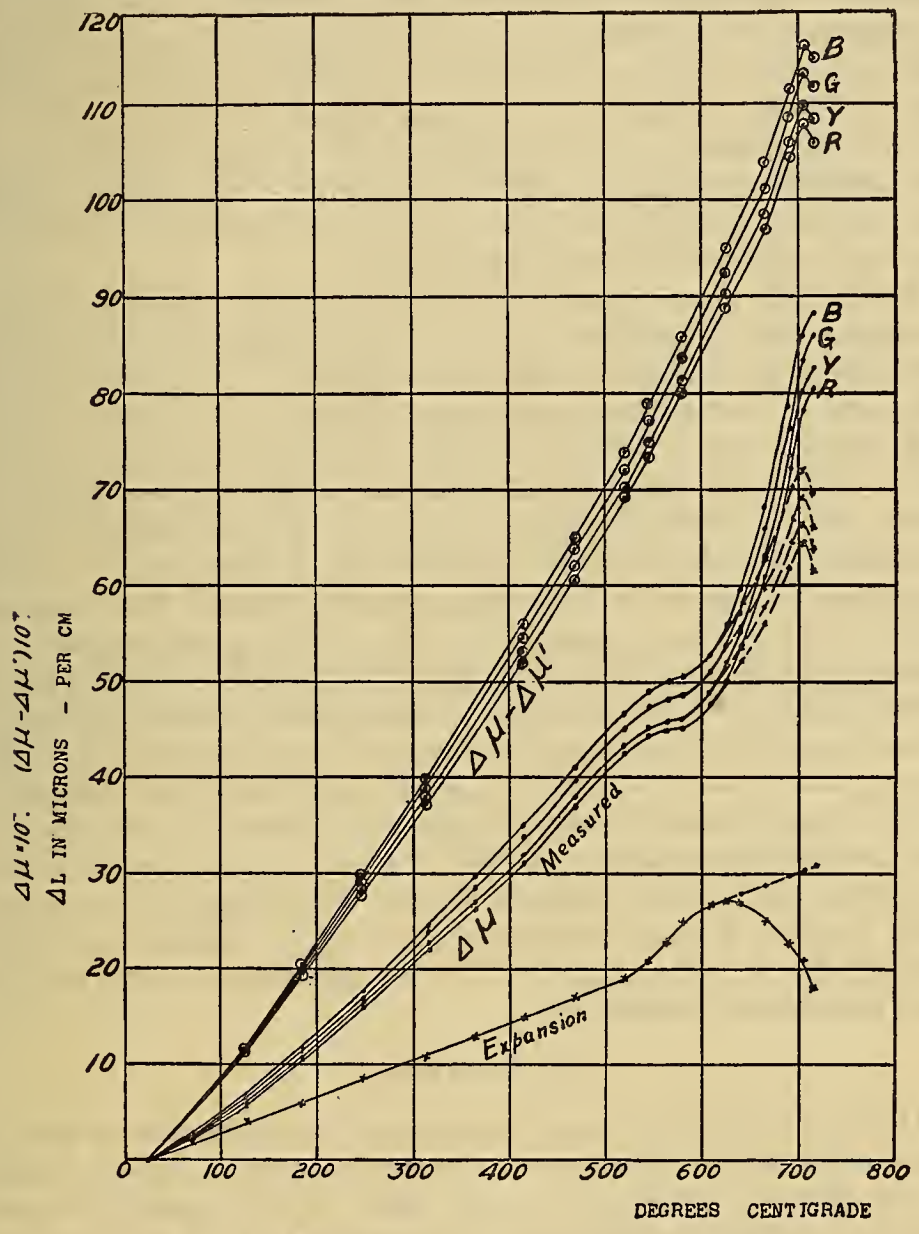

Fig. 14.—*Expansion and change in index of pyrex*

On applying corrections for the deformation to measurements of the expansion of the same glasses when heated at a constant rate it was found that their expansivities above the softening temperature must be nearly the same as below the annealing region. Assuming that pyrex acts in the same way, then the dotted part of the expansion

curve (fig. 14) represents the expansion of pyrex above 620° C. Using this expansivity to obtain the values of ΔN_v, the change in the index above 620° C. is represented by the dotted lines. These curves, which represent about the minimum values that $\Delta\mu$ could have, show that above the softening temperature the measured index again increased. The slight drop in the curves near 720° C. may have some significance and, together with the rapid increase just preceding, may in some way be related to the second increase in heat absorption which the measurements of Tool and Eichlin [10] show for pyrex. A joint investigation with Tool and Merritt has been undertaken for the purpose of making precise measurements of the density, expansion, refractive index, heat absorption, etc., of pyrex in this interesting region above the softening temperature.

The results represented by the curves of the figures show that changing the temperature of the different glasses produces similar changes in the physical properties considered. Each glass expands regularly up to the annealing region where a rapid increase in the expansivity and a corresponding rapid decrease in the density takes place. This rapid expansion continues until the glass begins to soften, which usually occurs near 600° C. The measured index of refraction increases with the temperature to about 450° C., then decreases as the density decreases rapidly through the annealing region, and increases again above the softening temperature. It seems probable that this change in index is the result of two opposing effects, a decrease caused by the decrease in the density and an increase caused by the increased absorption; or, to the same or a similar change within the atoms that causes the increase in the absorption. If lowering the density tends to decrease the index in accordance with the accepted index-density relation, then the curves marked $\Delta\mu - \Delta\mu'$ represent the increase associated with the change in absorption. This increase in index continues at a nearly constant rate even through the annealing region where the expansion is rapid and the heat absorption is enhanced.

VI. SUMMARY

Other measurements have shown that when transparent glass is heated from room temperature to the softening point radical changes in the physical properties occur. Thus, in the annealing region, which is usually near 500° C., the expansivity and heat absorption increase rapidly and the specific heat changes. The present investigation was undertaken to determine the changes in the index of refraction over a wide range of temperature. An interference method was devised by which the index of refraction can be accurately

[10] Tool and Eichlin, Jour. Amer. Ceram. Soc. 8, p. 1; 1925.

measured and any changes with varying conditions can be readily determined. A plate of the glass is placed in contact with two interferometer mirrors in such a way that two adjacent sets of interference fringes are visible, one produced by light passing through the glass, the other by light passing through an equal space in vacuum. The index at the initial temperature is determined from measurements made on the fringes and the distance between the reflecting surfaces. The change in index produced by increasing the temperature is determined from the number of fringes that pass a reference mark on the upper interferometer plate. Nine different samples of glass, including flints, crowns, and pyrex, were investigated. Measurements were made on the index of refraction and thermal expansion in the temperature region between 20 and 700° C. The results are represented by curves which show that the glasses passed through a critical expansion region near 500° C. in which the expansion rate increased by two to seven times. The index of refraction increased to this critical region, then decreased in the rapid-expansion region, and increased again above the softening temperature. It should be expected that the index would decrease with the density. In every case, however, the measured index was much larger than the index computed from the density relation $\frac{\mu-1}{d}=C$. This increase in the index with temperature is probably attributable to the same cause as that which shifts the absorption band toward the longer wavelength region.

Washington, October 21, 1925.